David Taylor Research Center

Bethesda, MD 20084-5000

EXPECTED CAPABILITY OF MULTIPLE - PROBE LDV PROPULSOR INFLOW MEASURING SYSTEM

by

Mark T. Coughran

David J. Fry

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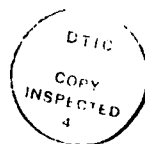
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ABBREVIATIONS AND SYMBOLS

D	body diameter
LDV	laser Doppler velocimeter
$\ell_{\text{blade passage}}$	propulsor blade passage length scale
$\ell_{\text{b.l. (integral)}}$	boundary layer integral length scale
ℓ_{maneuver}	maneuvering length scale
ℓ_{meas}	average model travel distance between two LDV measurements (Non-Scanned Mode); model travel distance between scans (Scanned Mode)
MASK	Maneuvering and Seakeeping Basin
n	vortex shedding frequency
R	propeller radius
St	Strouhal number
t_{meas}	average time between LDV measurements (Non-Scanned Mode); time between scans (Scanned Mode)
U	axial velocity
U_∞	freestream velocity
V	velocity normal to a cylinder
w	rotational speed

Greek Symbols

τ	time scale
θ	angular position (degrees)

ABSTRACT

The capability of the propulsor inflow velocity measuring system for a self-propelled model is projected. This system will provide the first measurements of the propulsor inflow field during maneuvering to support development of computational models of propulsor performance. *The proposed measuring system uses seven miniature laser Doppler velocimeter probes.* Temporal and spatial resolution that can be obtained with the system are estimated relative to flow time scales. Operation in both scanned and non-scanned modes is recommended. Measurement of the propulsor inflow field will be effectively instantaneous relative to the maneuvering time scale.

ADMINISTRATIVE INFORMATION

BACKGROUND

The DARPA Submarine Propulsor and Maneuvering Technology Program will provide a better understanding of the forces, moments, and acoustic behavior characterizing an underwater vehicle during a maneuver. Propulsor performance during the maneuver is particularly important, since it is a primary determinant of vehicle trajectory. Hydrodynamic measurements in this program will improve the reliability of and confidence in current analytical model predictions. For some maneuvers, flow predictions have not previously been possible. The flow phenomena isolated and defined by program measurements of axial and tangential inflow velocities and propulsor forces *should provide* the understanding needed to build new analytical models.

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The objective of Task 3.2 of the DARPA Submarine Propulsor and Maneuvering Technology Program is to measure the evolving wake flow into the propulsor of a self-propelled underwater model. Laser Doppler velocimetry (LDV) has been used in the past for similar wake flow measurements on non-maneuvering models[1,2]. A new, multiple-probe, miniature laser Doppler velocimeter measuring system is proposed for Task 3.2. It can rapidly scan circumferentially in a plane approximately one inch (25 mm) upstream of the forward hub face of the model propulsor. The proposed system, shown in Figure 1, uses three 1-inch diameter probes and four 5/8-inch diameter probes. The power and space constraints onboard the model require use of laser diodes and photodiodes in the LDV probes. To achieve adequate miniaturization of the model probes, frequency shifting was not initially considered an option. However, because of concern about directional ambiguity occurring during flow reversals, the possibility of frequency shifting using new technologies is being pursued.

LDV is inherently able to rapidly ($<10^{-4}$ s) measure flow velocity at one spatial position. The best system to quickly measure the propeller inflow field must:
1. incorporate as many probes as possible; 2. efficiently and continually scan their measurement points through a plane in front of the propeller. This is the basic rationale behind the proposed scanning miniature LDV measurement system.

It is of interest at this stage of the project to estimate the temporal and spatial resolution that can be obtained at the maximum model forward speed of 10 knots (5 m/s). The real system performance will depend greatly on signal quality resulting from the final probe construction, seeding environment, scanning speed, the particular maneuver, etc. The scanning measurement system also has mechanical design concerns, such as dynamic loads, that may affect measurement capability. As many of these concerns as possible will be

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addressed in this discussion. Some concerns will not be finally resolved until after measurement and model operation parameters are better defined. The probe construction and seeding environment will be evaluated in a benchtop test flow facility. This facility, to be built by a contractor as part of other work, will provide a low-turbulence water flow with an accurately known velocity.

ANALYSIS

For simplicity, and to illustrate one of the various ways in which the system could be configured, this discussion is primarily concerned with measurement of the axial velocity component at two radii, as shown in Figure 1. This is the velocity component not measured by the other program tasks. The tangential velocity could alternately be measured by any of the probes. Mechanical driving of the probes in the scanning mode will add a small uncertainty to the tangential velocity measurements. However, there will be no directional ambiguity in the tangential component since the scanning (if at sufficient speed) is equivalent to frequency shifting for this component. In the configuration discussed here, the three larger probes are trained to an outer radius approximately equal to the propeller radius, 0.15 m, and the four smaller probes are trained to a lesser radius, e.g. half the propeller radius.

The term "effective scan rate" will be used in this report to mean the rate at which a measurement is repeated at a fixed point relative to the model. The measurement can be repeated by the same probe or a different probe that is scanned into the same position. The effective scan rate fixes the maximum velocity fluctuation frequencies that can be adequately sampled. Another term "scan speed" is the actual tangential velocity of the LDV probe measurement volume at the configured radius. Measurement accuracy of

individual LDV data points will decrease with scan speed. In backscatter LDV, accuracy is generally no better than 0.5 to 1.0% of the relative velocity between the local flow and the scanning measurement volume. Measurements of the axial velocity component will have significantly reduced accuracy when the (tangential) scan speed exceeds the (axial) flow velocity.

The effective angular scan rate will be faster at the inner radius, where the circumference is subdivided by four probes. The focus here is on the limitations of measurement at the outer radius where three probes give a slower effective scan rate (less time resolution) and a faster scan speed (less measurement accuracy). Other configurations can allow more than two radii to be measured in one setup. A tradeoff is always available between number of radii covered and the rate at which all circumferential locations can be scanned.

PROPELLER INFLOW VARIATION

LDV measurements will be taken at one axial location or measurement plane (in the model frame of reference). This is very similar to traditional wake surveys taken in towing tank facilities to assist propulsor design work. In that one cross-sectional plane, the velocity will vary spatially (with radial and circumferential position) and temporally as the maneuver proceeds.

The following discussions will focus on the three primary sources of spatial and temporal velocity variations. The first source is the nearby propulsor that changes the flow at any given location with each passing propeller blade. This will be referred to as propulsor induced flow. The second source is the collection of turbulent structures that comprise the thick boundary layer at the aft end of the vehicle. These first two sources

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account for the spatial and temporal flow variation found in traditional towing tank wake surveys.

Maneuvering adds a third source of variation to the wake flow. Changes in vehicle movement direction, orientation to movement direction, and propeller RPM will greatly affect flow velocities at the measurement plane. These changes occur through many mechanisms. Some mechanisms are direct such as the creation of vortex structures from hull or appendage angles of attack to the flow. Other mechanisms operate by changing the nature of the first two sources of velocity variation. Boundary layers develop very differently on a vehicle oriented with either a non-zero angle of attack or changing angle of attack to the flow. Propeller blade performance and hence induced flow are dependent on propeller inflow characteristics. These characteristics are being continually changed by the maneuver.

TIME SCALES

An LDV system expected to measure a spatially and temporally varying flow must measure the flow field "faster" than "significant" changes can occur. Estimates of the time required for significant flow field changes are referred to as time scales of the flow field. Time scale estimates are needed for each of the flow variation sources: maneuvering, passage of turbulent boundary layer structures, and propulsor induced velocities. The magnitude of these time scales can be estimated as follows.

The largest and most easily measured time scale is due to the maneuver itself. One may think of this in terms of the rate of change of the model motion or in terms of the unsteady vortices which comprise the gross, immediate effect on the flow field. A crude estimate of the time scale of the vortices shed from the body is obtained by referring to

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the related situation of a cylinder in steady crossflow. The Strouhal number is defined as

$$St = \frac{nD}{V} \qquad (1)$$

where n is the frequency of vortex shedding, D is the cylinder diameter, and V is the velocity normal to the cylinder. The Strouhal number is known to have a value of approximately 0.2 over a wide range of Reynolds numbers[3]. Here a cylindrical body is imagined turned at 30 degrees to a freestream velocity of 10 knots (5 m/s), and the time scale is taken to be the inverse of the shedding frequency. Using D equal to the body diameter (0.6 m) and V equal to the crossflow component (10 knots $\times$ sin(30 degrees)), a time scale $\tau_{maneuver}$ of 1200 ms is estimated. Alternately, in terms of the model motion, two extreme maneuvers may be considered. Previous data indicate a maximum rate of change of yaw angle in the range of 15 to 30 degrees/s for a model approach speed of 10 knots (5 m/s). To calculate a time scale of significant velocity change, a model is imagined starting at zero yaw angle in a steady flow field. The axial velocity is reduced by approximately the cosine of the yaw angle, so that an 18 degree turn is required to affect the axial velocity by 5 percent. This will require somewhere between 600 and 1200 ms of maneuver time for the turning rate range given above. Finally, a maneuver time scale can be defined by the model deceleration in "crash-back" maneuvers. Previous data indicate that a 5 percent reduction in axial speed can occur in the range of 1000 to 2000 ms. The three maneuvering time scale estimates are of similar magnitude. The shortest estimate, 600 ms, will be used in subsequent discussions.

The largest or integral length scale of the boundary layer, $\ell_{b.l.\ (integral)}$, is on the order of the boundary layer thickness. For the present estimates at the stem, this will be

approximated by the maximum body radius, D/2, of 0.3 m. An integral time scale is obtained by adopting Taylor's hypothesis[4], in which the turbulent motion is assumed to be frozen as it passes over a fixed probe at some convection velocity U. Then

$$\tau = \frac{\ell}{U} \approx \frac{D}{2U_\infty} \qquad (2)$$

where U is taken to be the freestream velocity, U_∞, or 10 knots (5 m/s). The resulting integral time scale estimate is $\tau_{b.l.\ (Integral)} \approx 60$ ms. The turbulent microscales generally depend on the Reynolds number but would be orders of magnitude smaller and more difficult to resolve.

The time scale of propulsor induced velocities is the time required for passage of a propeller blade by a fixed measurement point. A minimum value of this time scale can be calculated based on a maximum model propeller RPM of 800. If a propeller blade effectively occupies an angle of 10 degrees, the resulting time scale is approximately 2 ms.

The maneuvering time scale is respectively one and two orders of magnitude larger than the time scales of the other two sources of flow variation. This indicates that while maneuvers may be affected by individual maneuvering time scale phenomena, they are not affected by normal boundary layer structures or individual propeller blade passages (with much shorter time scales). Vehicle maneuvers are impacted only by the net effect of the many boundary layer structures and propeller revolutions that occur within any period of maneuvering time scale duration. These time averaged quantities include mean velocity, velocity standard deviation, and other statistics that require updating several times during a maneuvering time scale period. The same argument does not follow for propulsor generated noise at frequencies corresponding to the short boundary layer time scales.

MEASUREMENT SYSTEM CAPABILITIES

The measurement system is expected to operate in two distinct modes. It is necessary to quickly scan the LDV probes circumferentially to provide full coverage of the propulsor inflow during a single model maneuver. However, the probes cannot be scanned rapidly enough (while retaining adequate precision) to capture all expected velocity fluctuation time scales. Therefore a second operation mode will be employed initially to measure and characterize these fluctuations at a limited number of measurement locations.

In this "Non-Scanned" operation mode, the seven LDV probes will remain stationary relative to the maneuvering model. The data gathered can be used to check velocity fluctuation magnitude and time scale assumptions. The data should also allow separation of propulsor induced velocity fluctuations from data sets gathered in the scanned mode.

NON-SCANNED MEASUREMENTS

In order to better document velocity fluctuations at all expected time scales, it is recommended that a set of measurements be made with the probes stationary within the maneuvering model. To "freeze" the motion of a typical flow structure or fluctuation, it is assumed that approximately 10 measurements must be made during passage of that structure. Assuming that good seeding can be obtained compatible with the other project tasks, signal quality should be comparable to previous towing tank experiments[1] using small fiber optic probes. Taking speed differences into account, it is reasonable to expect a mean LDV data rate of 1200 measurements per second. This preliminary estimate will be checked in the test flow facility using water from the Maneuvering and Seakeeping Basin (MASK).

In the non-scanned mode, measurements are repeated at a given location (relative to the model) at the LDV data rate or 1200 Hz. The average time window for 10 measurements ($10 \times t_{meas}$) is then approximately 8 ms. Time scales longer than 8 ms should be resolvable in this operation mode.

Maneuvering Time Scales

From the previous section, it is clear that the maneuvering time scale (600 ms) can easily be resolved by non-scanned measurements. Figure 2 illustrates the relationship between measurements and the various scales of velocity change. For illustration purposes, the flow time scales already derived have been converted to length scales by multiplying by a forward model velocity of 5 m/s. The length scales can be thought of as the travel distance of the model during the corresponding time scales. The minimum length scale that can be readily resolved under this operation mode is 10 times the average travel distance of the model between LDV measurement points, "$10 \times \ell_{meas}$". It is calculated simply as the product of $10 \times t_{meas}$ and the forward speed of 5 m/s, or 0.04 m.

Boundary Layer Time Scales

From previous sections, it is clear that the boundary layer integral time scale can be resolved by non-scanned measurements. This is illustrated in the comparative length scales of Figure 2. Some smaller boundary layer time scales will also be measurable. The theoretical time scale limit is twice the sample time or 1.7 ms. As stated previously, the smallest boundary layer time scales or microscales are expected to be too short to resolve by LDV. The amplitude of these high frequency fluctuations is also expected to be less than the LDV's velocity resolution of about 1% of the freestream velocity.

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Propulsor Induced Flow Time Scales

Propulsor induced velocity fluctuations (time scale $\approx$ 2 ms) cannot be directly measured for each propeller blade passage. However, with a steady inflow, propulsor induced flows repeat at the propeller blade rate. This fact is used routinely at many facilities including DTRC[2] to examine flows between and even in the boundary layers of spinning propeller blades. Measurements taken over many blade passages and propeller revolutions are ensemble-averaged based on the propeller position at the exact time of measurement. In this way data rates of 100 or fewer samples/s were adequate[2] to define a propeller blade boundary layer passing a fixed LDV measurement point in about 0.5 ms.

Experiments by the authors* have used the same technique to define propulsor induced velocities for a towed model test. Here the model motion was steady for a 15 second towing carriage pass. However, random boundary layer flow fluctuations, similar to those described here, were present and averaged out of the data taken at each propeller location. The propulsor induced flow of the five bladed propeller is clearly visible in the measured data shown in Figure 3.

It should be noted that frequency of measurements is not the only concern. In order to be measurable, the fluctuations of interest must be larger than the LDV measurement accuracy. At the plane of measurements chosen for the model experiments, propulsor induced velocity amplitudes are expected to be only about half those in Figure 3.

Over a fraction of the maneuvering time scale, say 200 ms, the data for this experiment can be handled in the same way as previous towed model tests. The shorter sample time can be offset by the higher data rate of this experiment and by assuming

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* Unpublished wake survey by D. Fry, September, 1987.

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identical propeller blades. The result of a single probe's data for non-scanned measurements during a maneuver should be amplitude, phase, and wave form estimates of the propeller induced flow every 200 ms (during the entire maneuver). This information will be available at seven different radial and circumferential positions for each run. Successive runs will be performed to take data at every radius of interest. Circumferential variations of induced flow amplitudes and waveform will result only from nonlinear interactions with the wake. These latter variations are expected to be minimal and will be measured only to the extent necessary to reduce mean velocity estimation errors to below 1% of the freestream velocity.

Accuracy and Spatial Resolution

Based on previous experience in the Deep Water Basin using probes with similar final lenses, measurement accuracy of individual LDV data points can generally be expected to be about 1% of the freestream speed of the model. The actual value will depend on the final LDV probe design and MASK particle seeding. Because there is no frequency shifting in the probe as currently planned, portions of a few maneuvers with axial flow reversals will yield ambiguous data--the direction of the measured velocity will be uncertain. The tangential velocity component is likely to have direction reversals in all maneuvers. For this reason most, if not all, non-scanned measurements will be of the axial velocity component.

Spatial resolution in the non-scanned mode is entirely a function of LDV measurement volume size. The dimension in the circumferential and axial directions is expected to be approximately 0.2 mm. The radial dimension is expected to be approximately 2 mm.

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Summary

The non-scanned operation mode can measure at seven locations during each model maneuver run. It is therefore inadequate for defining the propulsor inflow field unless many (100+) model runs are made in which the maneuver and associated velocities are accurately repeated. At those seven locations, however, sufficient data are sampled to generate statistically significant estimates of the velocity mean, standard deviation, etc. over periods that are a fraction of the maneuvering time scale. Spectral analysis of single location time histories can reveal vehicle boundary layer fluctuation frequencies and associated amplitudes that are locally present during the maneuver. Finally, if propulsor induced flow fluctuations exist with measurable amplitude at the plane of measurements, the repetitive nature of these fluctuations should allow their definition during the maneuver in terms of amplitude and form.

SCANNED MEASUREMENTS

The primary interest in flow measurements of this project task is to define the inflow over the entire propeller plane at each "instant" during the model maneuver. Such flow field results are needed in evaluating propeller performance and the spatial harmonic contribution to propulsor noise. Non-scanned measurements taken over many exactly repeated model maneuvers could to some extent satisfy this need as different locations could be taken on different model runs. This is not the desired or expected primary mode of operation because of finite model operation repeatability, random flow pattern components, and experiment expense considerations.

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Maneuvering Time Scales

To provide "frozen" surveys of the evolving flow, it is assumed that a complete circumferential scan must be measured in approximately one tenth of the appropriate time scale. Considering only the maneuvering time scale, a scan period, t_{meas}, of approximately 60 ms is required. For the three probe volume positions shown in Figure 1, a scan will be completed on the average with every 120 degrees of LDV traverse motion (at large radii with 3 large LDV probes). The LDV probe traverse then must scan or spin at about 5.5 revolutions per second. This also means a probe volume scanning speed of about 5 m/s for measurements at the propeller radius. Scanning speeds at smaller radii are proportionately less.

Figure 4 illustrates how each angular position is covered in the scan measurement time, t_{meas}, of 60 ms. Because probes 1, 3, and 6 are not located an equal angular distance apart, this is an average time between measurements at a given angular position. Alternately, Figure 5 shows how the probes move in helical paths in a stationary frame of reference. The flow fluctuation length scales (based on the model speed of 5 m/s) are shown in Figure 6 juxtaposed to the helical scan paths. The wake survey, occurring as the model moves a distance ℓ_{meas}, is effectively instantaneous relative to the maneuvering length scale ($\ell_{maneuver}$).

Boundary Layer Time Scales

The probes move a significant distance axially during a scan relative to the boundary layer integral scale. It is unlikely that many boundary layer related flow fluctuations can be adequately sampled in a scanned mode of operation. However, as stated previously, non-scanned data sets should determine the general amplitude/frequency

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character of these flows during the maneuver. Based on that characterization, it may be found that some scanned mode configurations will allow marginally adequate sampling. It is much more likely that multiple scans will be averaged together. These scans will be taken on one or more model runs during particular time segments of $\tau_{maneuver}$ duration. The series of averages is the mean flow into the propulsor as it changes only over the maneuvering time scale. Standard towing tank wake surveys perform this same time scale averaging of boundary layer fluctuations by virtue of the pitot tube sensor response time. Boundary layer velocity fluctuations can still be partially characterized by the scanning LDV probes. Standard deviations and other statistical quantities can be derived from the multiple measurements on separate scans.

Propulsor Induced Flow Time Scales

Resolution of 2 ms propulsor induced flow fluctuations is not possible in the scanning mode (Figure 6). However, the portion of scanned mode velocity measurements attributable to propulsor induced flow fluctuations can be derived from previously described non-scanned data and knowledge of the exact measurement and propulsor position.

Each LDV measurement and position reading will require less than 10^{-4} seconds. Propeller position can then be determined to better than 0.5 degrees and measurement position to better than 0.2 degrees. Knowing measurement position, propeller position, and the propeller induced flow fluctuation data (amplitude, phase, and function shape), an estimate of propulsor induced flow fluctuation velocity for each scanned measurement can be calculated. This fluctuation velocity, which has an average value of zero, can be used to "subtract out" the propulsor fluctuation. This will leave individual velocity measurements that are independent of the exact phase relationship between the propeller

position and either the model maneuver or flow field phenomena. Propeller performance estimates and spatial wake harmonic analysis require data in this form.

Accuracy and Spatial Resolution

As stated previously, measurement accuracy of individual LDV data points can be expected to be about 1% of the freestream speed of the model. This is dependent on the final miniature LDV probe design and maneuvering basin particle seeding. As in the non-scanned mode, the axial velocity measurements will be susceptible to directional ambiguity during flow reversals. In scanned mode operation, however, the tangential velocity component will have no ambiguity for reverse flow speeds up to the scanning speed (5 m/s at the propeller radius).

Scan speed increases have the effect of increasing the number of waterborne particles encountered by the moving LDV measurement volume. This increases the sensor's data rate; however, the average particle will cross fewer measurement volume fringes due to decreased particle residence time[5]. This sets an upper limit on scan speeds since measurement accuracy decreases as fringe crossings are reduced. The circumferential spatial resolution is also reduced with increased scanning speed. The increased data gathered in a given time are more than offset by the increased distance the measurement point is scanned. The proposed scanning rate of 330 RPM (i.e. 120 degrees in 60 ms) means that the maximum scanning speed is no more than the model speed of 10 knots (5 m/s). This results in a fringe crossing reduction of only about 30% at the outermost measured radius and less at smaller radii. Taking previous experience[1] into account, it is reasonable to expect that each probe will encounter on the order of 72 particles in a 60 ms scan of 120 degrees. This places data points 1.7 degrees apart on the average. The axial

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and radial spatial resolution, as in the non-scanned measurements, are expected to be about 0.2 and 2.0 mm respectively.

Summary

The proposed scanning LDV system can capture maneuvering time scale changes at a complete set of circumferential positions. At least two and as many as seven radii can be recorded on one model maneuver. The estimated spatial resolution of under 2 degrees is adequate for propulsor performance and spatial harmonic analysis. Non-scanned data are required to make scanned LDV data independent of propeller revolution phase.

Multiple model scanned runs will allow estimation of velocity variation statistics (e.g. standard deviation) at any measurement plane position. These standard deviations and other statistical quantities should match those measured at only a few locations in a non-scanned operation mode. Given proper data analysis, differences will illuminate the extent to which velocity fluctuations of model maneuvers are repeatable.

DATA ANALYSIS

Data acquired with the non-scanned probes at various angular and radial positions will be used to verify data rates obtainable under scanned conditions. Time histories will be plotted and used to verify the time scales of the flow and indicate the appropriate scanning speed.

Scanned mode data require significant analysis to find the evolving wake surveys needed for propeller performance and spatial harmonic estimates. LDV measurements occur at randomly spaced particle arrival times. For the mean data rate stated above, a scan across 120 degrees in 60 ms will result in an average angular resolution of

approximately 1.7 degrees. A hypothetical data set for one half of a circumferential scan (only a small segment of the data record which would be obtained during each maneuver) is shown in Figure 7. The graphed LDV data are typical of a nominal case with four appendages and the largest appendage located at 0 degrees. The spatial resolution should be adequate, unless much larger unanticipated gradients occur.

Some method of interpolating or smoothing the data will be necessary. Simple interpolation of the raw data would be adequate for high data rate and low noise. However, this could introduce artificial frequency components if precision uncertainty turned out to be similar in magnitude to the nominal case shown in Figure 7. The problem has been studied by other investigators. The more sophisticated methods appearing in the literature[6] would add considerably to the computational overhead, and would make rapid data analysis more difficult.

The data in Figure 7 must first be interpolated in space to estimate velocities for equally spaced circumferential locations. Figure 8 shows an example interpolation of a small segment of the data in Figure 7. Equally spaced data are generally required as input to propeller performance and spatial wake harmonic analysis programs.

Figure 4 shows how time records could be interpolated for a chosen angular position. The dots represent the velocity at a particular location, 85 degrees, at a number of instances in time. The dots nearest the vertical "wake survey" line will be used to interpolate a velocity at the exact wake survey time of, for example, 160 ms. This procedure assumes that the spatial data interpolation (for 85 degrees at least) has already been done for the relevant scans. A complete and useable wake survey requires interpolating all positions (circumferential and radial) in this way for the same point in time (at 160 ms). Potentially an independent wake survey could be derived for about

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every 60 ms period of the maneuver on the two radii measured in this particular scanning mode configuration.

PROPOSED TEST PLAN

Each model maneuver planned for investigation will require multiple runs to collect adequate LDV propulsor inflow data. In addition to considering what amount of data is adequate, model operational procedures will impact any well thought out test plan. Changes to LDV probe radial measurement locations may require access to the interior of the model. Operational mode changes will probably also require similar access. These experimental apparatus changes are most efficiently accomplished during model battery charging or over inactive work shifts. Circumferential position changes in scanned or non-scanned modes can be accomplished between model runs.

A *set of model runs* is defined as the multiple runs of the studied maneuver accomplished on a single model battery charge. Multiple runs will be desirable initially to ensure a sufficient sample size, since the standard deviation of flow fluctuations and number of flow "cycles" measured in one run are unknown in advance. Use of a single battery charge for several repeats of one maneuver appears convenient in view of a companion program task involving particle displacement velocimetry. For that task, it may be impractical to perform different maneuvers (requiring different light sheet positions) within one battery charge. Furthermore, because the range of light sheet coverage is about the same as the trajectory uncertainty, several runs may be required to successfully repeat a desired maneuver trajectory.

A minimum of one set of runs is required in a non-scanning operating mode. Each of the seven probes will be positioned at a different measurement radius. After each run, a

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circumferential position change will be made. At the end of the set of runs, the data will be examined to determine if an additional non-scanned set of runs is required. Criteria considered will be general data quality and whether the circumferential positions covered adequately define propulsor induced and boundary layer scale velocity fluctuations. The first maneuver measured with this technique will be treated very conservatively with respect to the latter criteria. Judgements on subsequent maneuvers can probably be made more intelligently. Ten may be an adequate number of non-scanned runs for the average maneuver. This might be one or two model battery charges.

In the scanning probe operation mode, a minimum of two and a maximum of seven radii are measured on each model run. Assuming the minimum number (as in most of this paper) and measurement radius changes only between battery charges, four battery charges will be required for each maneuver. This test plan allows for multiple runs with the probes remaining at identical radii. This should be useful, given adequate model run repeatability, in averaging out boundary layer related flow fluctuations over maneuvering time scale periods.

Thus, a first attempt at a test plan calls for five to six sets of model runs (or five to six battery charges) per studied maneuver. A minimum of five executions of that maneuver per model run set (or battery charge) is assumed by this estimate.

CONCLUSIONS

Several configurations of the proposed multiple-probe LDV system have been analyzed. Using the configuration mainly discussed in this report, it appears that the maneuvering effects on propulsor inflow can be efficiently measured with a scanning set of LDV probes. Boundary layer produced velocity fluctuations do not appear to be efficiently

measurable over the entire propeller inflow plane. However, spatially limited measurements (in a non-scanned operation mode) will define the frequency spectrum of these fluctuations below 100 Hz. Propulsor induced flow fluctuations can be defined in a non-scanned probe operation mode. With this information, each scanned probe measurement can be decomposed into a propulsor induced fluctuation velocity and a velocity independent of propulsor induced fluctuations.

It will be desirable to conduct initial maneuvering runs with the probes not scanned, followed by scanning runs. Non-scanned probe data will allow an optimum tradeoff to be made between scanned radii and effective scanning rate. Furthermore, velocity fluctuations which are not expected to be measurable in scanned systems runs can be measured in detail at a limited number of locations. Scanning speed and hence effective scan frequency are limited by measurement accuracy considerations. Mechanical design limitations, data transfer, and storage requirements may also be factors.

ACKNOWLEDGEMENTS

Section A–A

SCAN
DIRECTION

1–7 LDV Probes
 8   Projected Measurement Points
 9   Rotating LDV Traverse
10   Propeller Shaft (.5 in.)
11   Stationary Hull
12   Hull Appendages

$\omega_{LDV} \neq \omega_P$
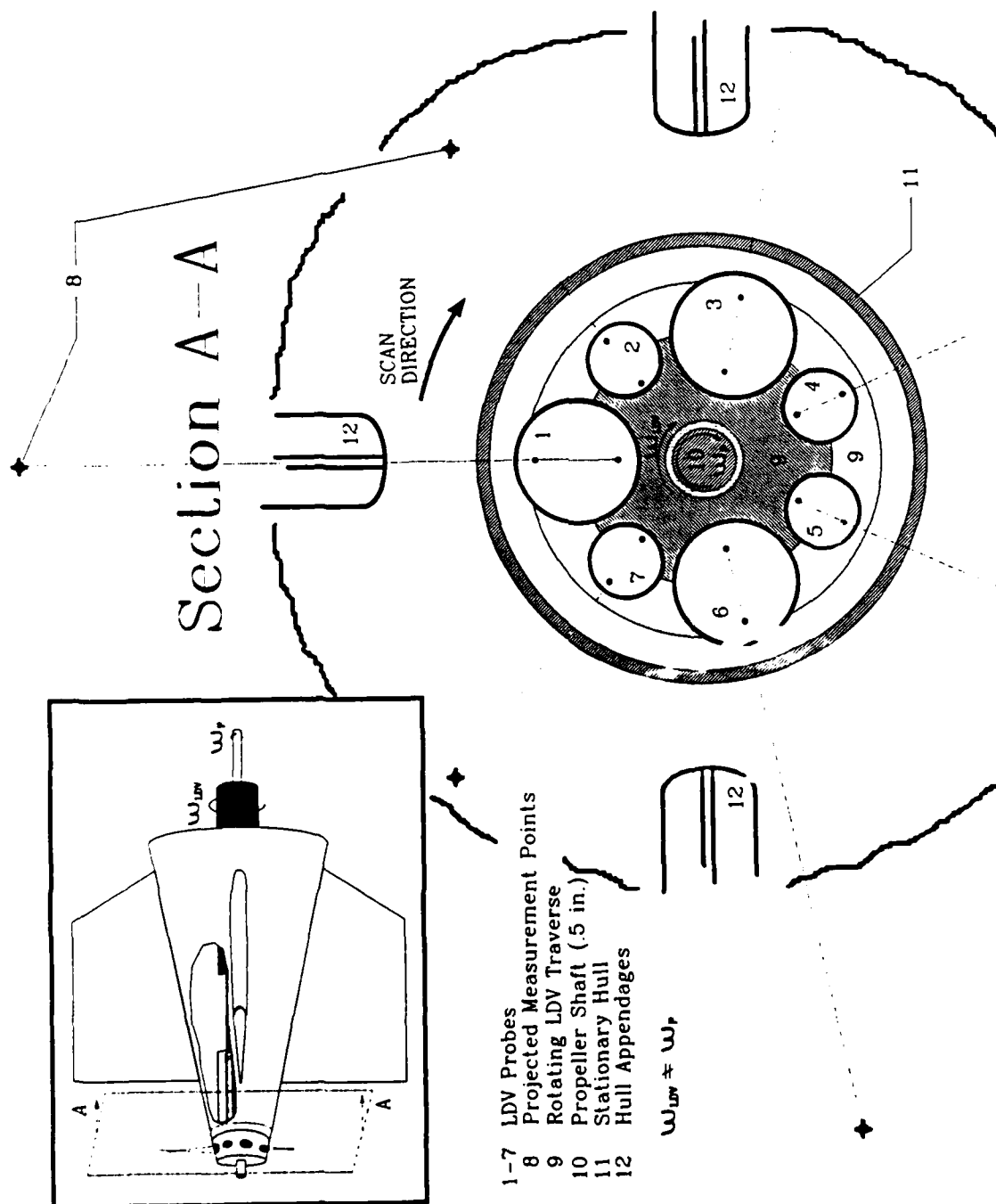
Figure 1. Multiple-probe scanning LDV measurement system.

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$\ell_{\text{blade passage}}$

$\ell_{\text{b.l. (integral)}}$

ℓ_{maneuver}

$10*\ell_{\text{meas}}$
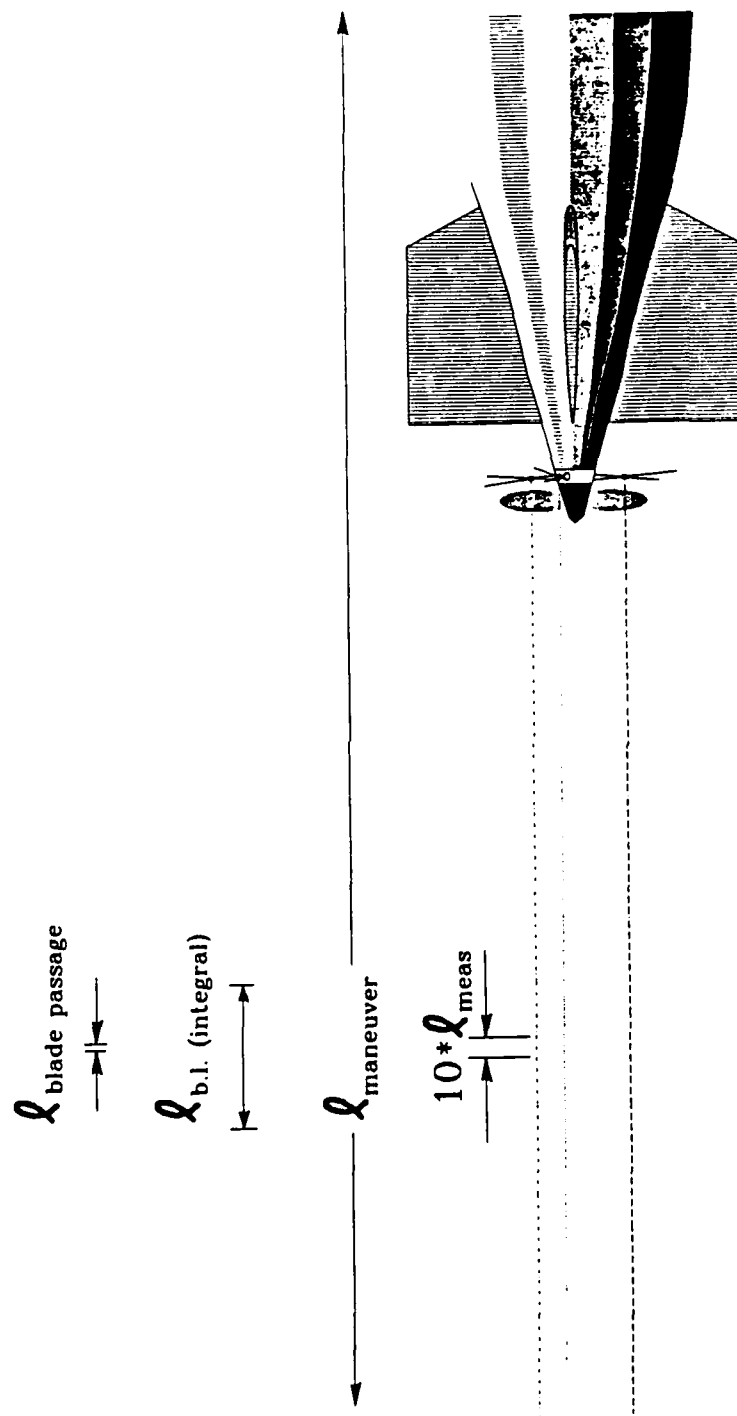
Figure 2. Non-scanned mode LDV measurement capability.

22
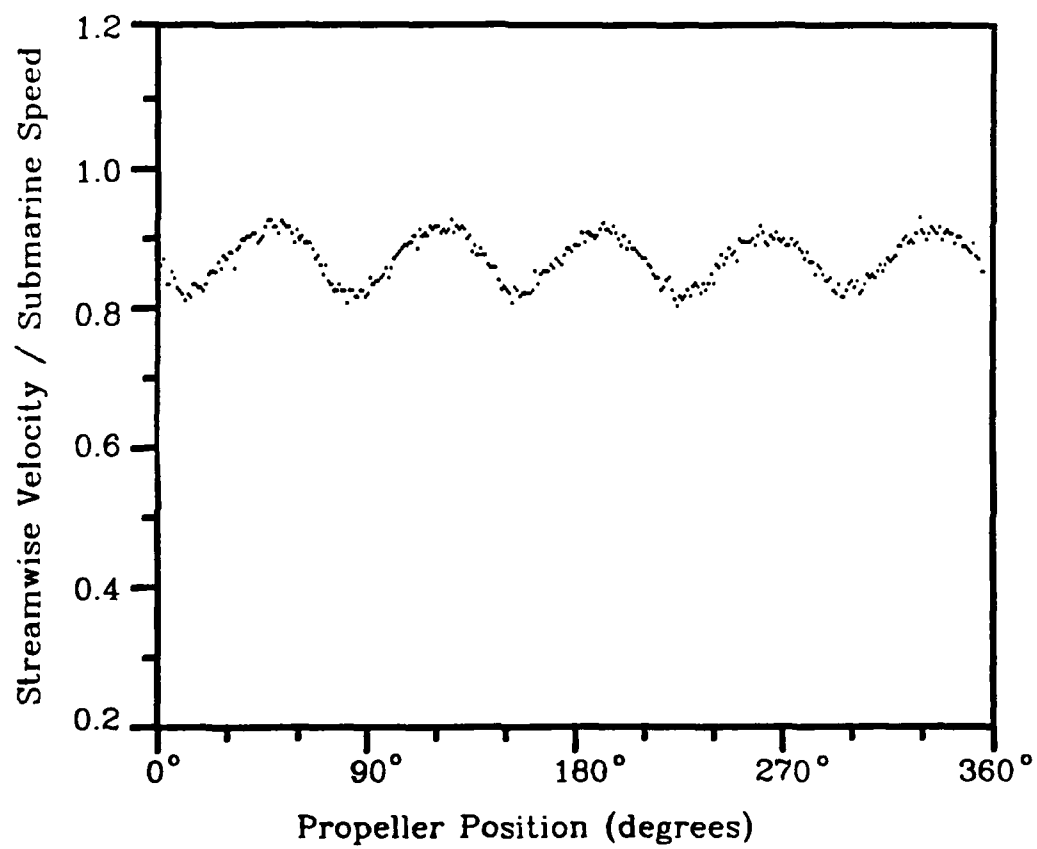
Figure 3. Measurement of propulsor induced velocity fluctuations.
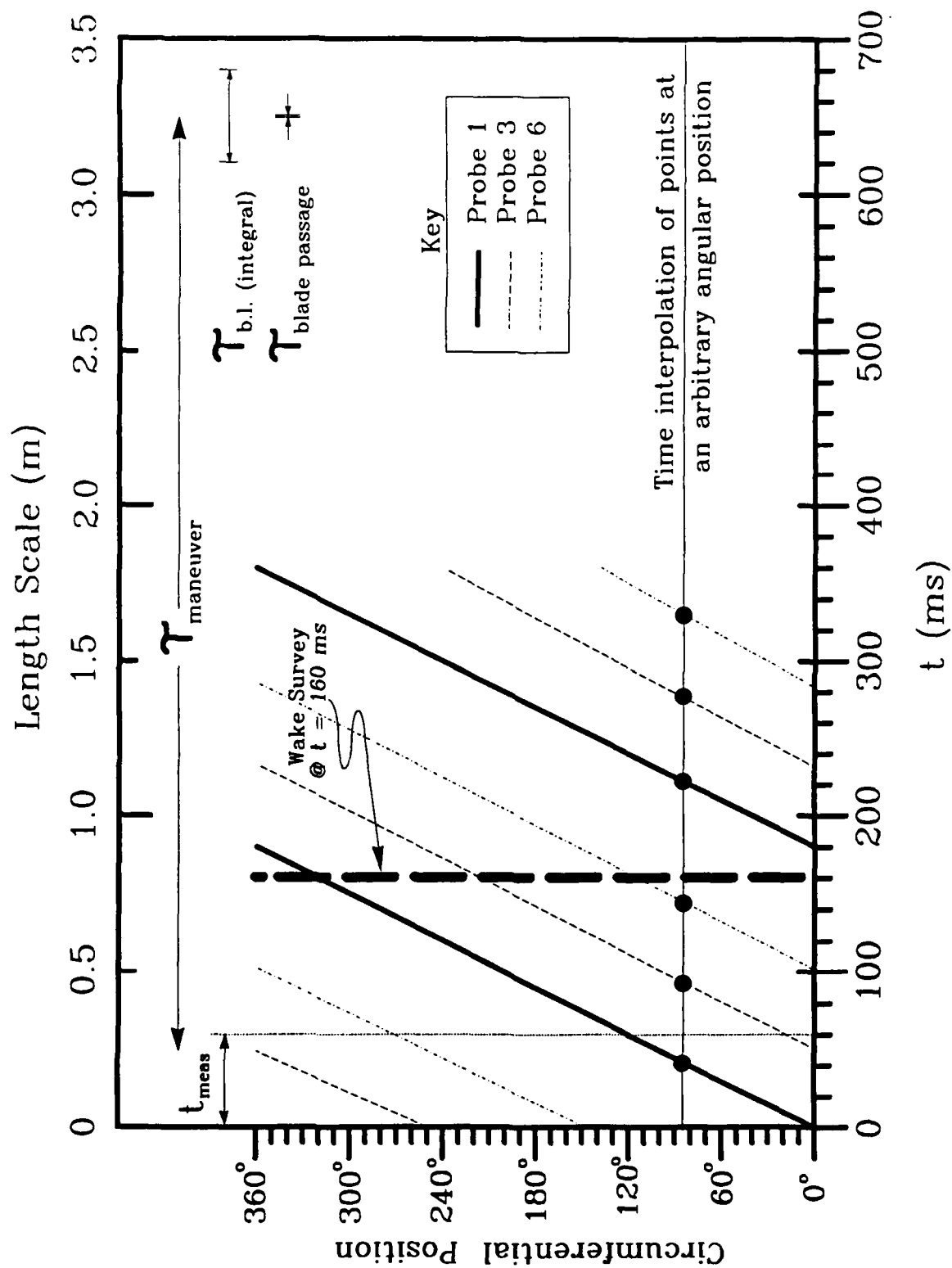
Figure 4. Angular coverage and temporal resolution of scanned mode LDV measurements.
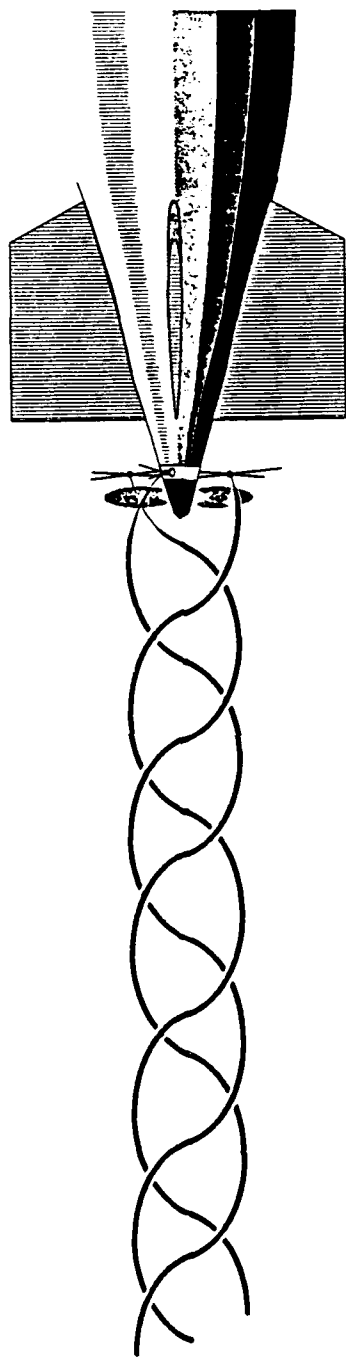
Figure 5. Helical paths of scanned mode LDV measurement points (large radius only).
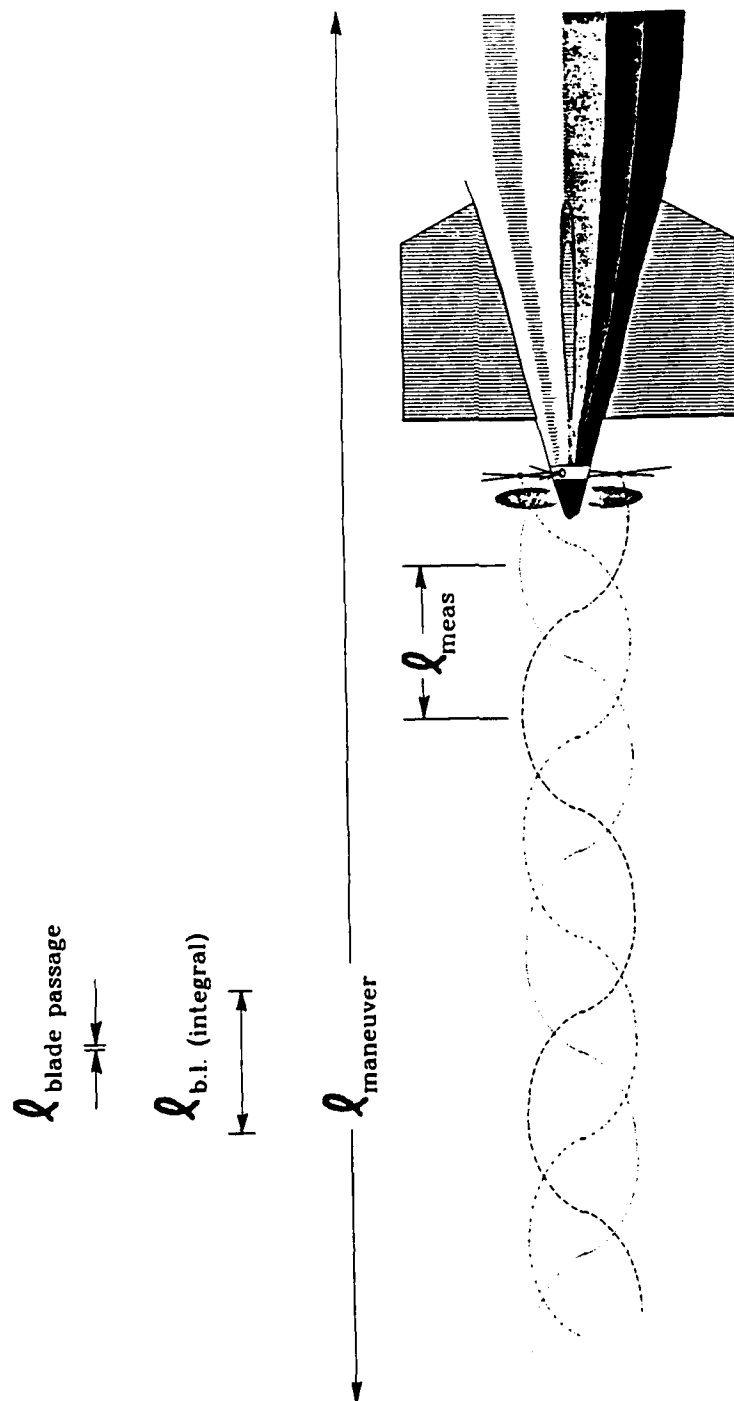
25

Figure 6. Scanned mode LDV measurement capabilities.

$\ell_{\text{blade passage}}$

$\ell_{\text{b.l. (integral)}}$

ℓ_{maneuver}
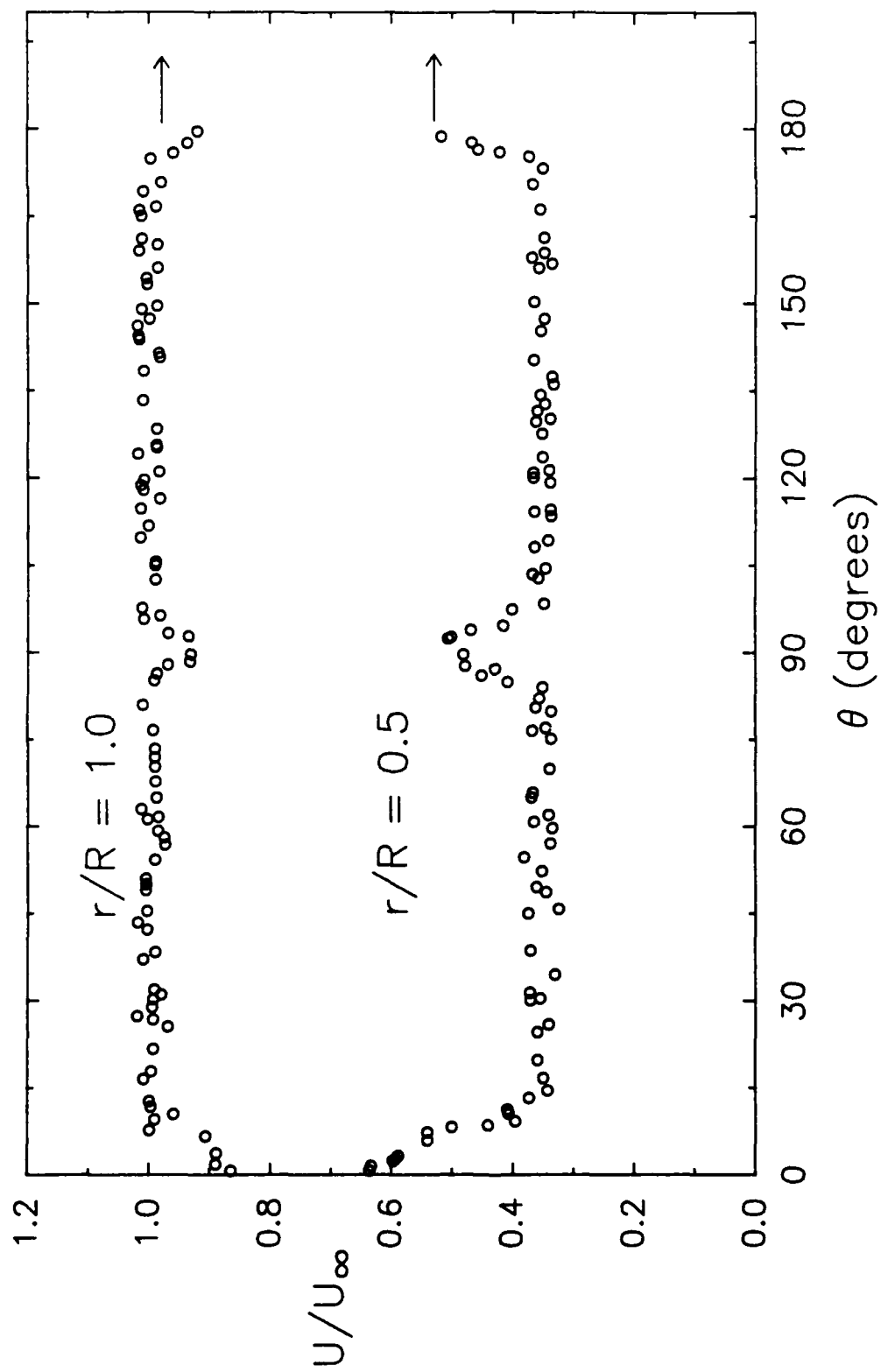
ℓ_{meas}

26

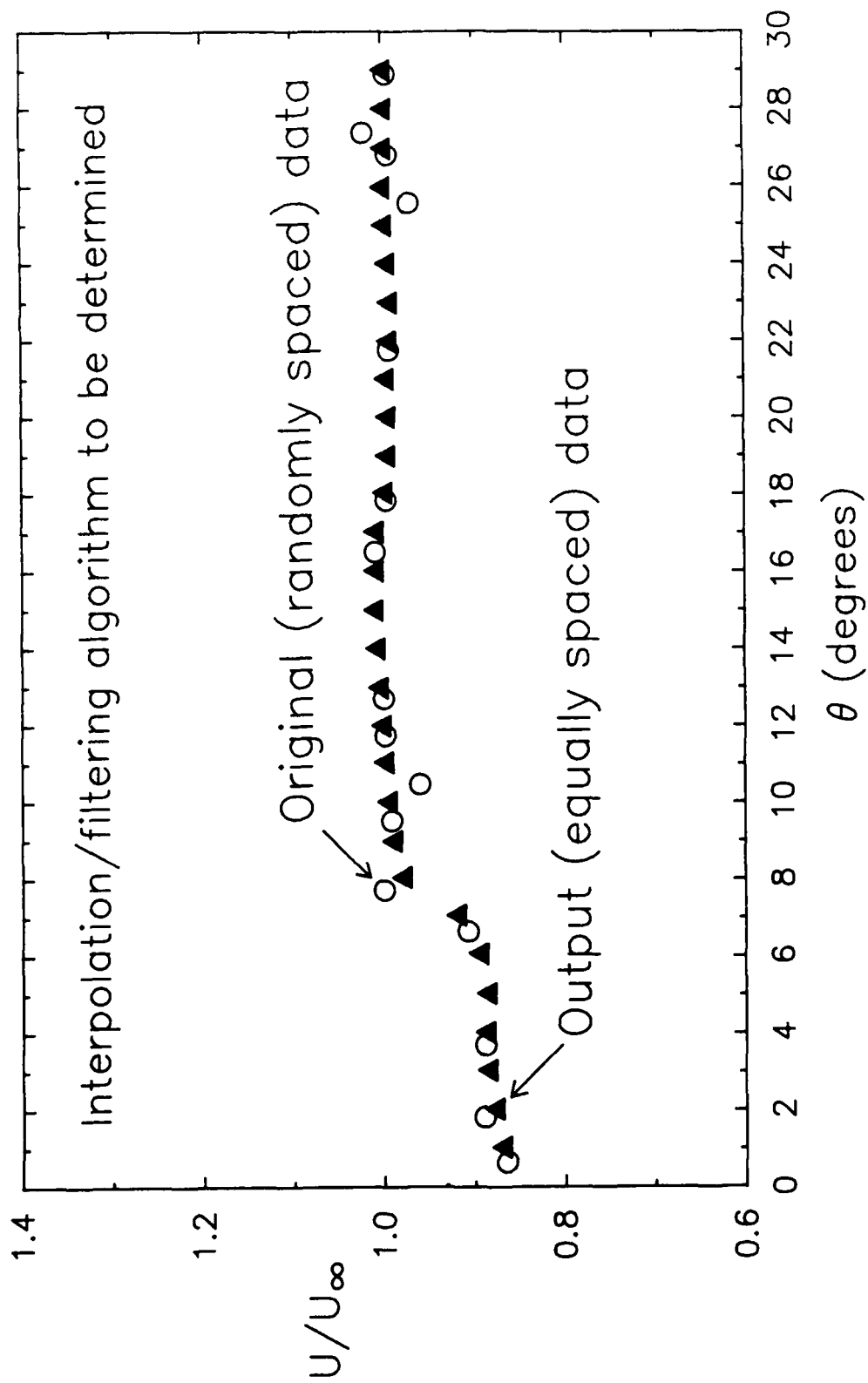Figure 7. Hypothetical LDV probe data segment.

Figure 8. Spatial interpolation of randomly occurring LDV measurements.

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